Operational Characterization of a DFIG Wind Turbine Using SCADA Data and dq-axis Torque Analysis

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Abstract. This paper analyzes SCADA measurements from a DFIG-based wind turbine and extends them with a dq-axis torque interpretation. We detect controlled shutdown and high-output phases, quantify speed-power correlations, and visualize operational regimes that are consistent with control regimes. The dataset exhibits a shutdown window followed by a restart to peak output (2.62 MW) and a prolonged low-power interval. Findings are discussed against the stator-flux-oriented torque equation, highlighting controller behavior under variable wind.

INTRODUCTION

Doubly Fed Induction Generators (DFIG) dominate modern onshore wind fleets owing to their cost-performance balance and grid support capabilities. Understanding their operational regimes from SCADA data is essential for reliability, control tuning, and performance assessment. This work follows a Scopus-style structure to report empirical characteristics of a DFIG turbine and interpret them using dq-axis torque theory [1-6].

When writing the DFIG dynamic equations [7-10]:

Mechanical torque:

$$T_m = \frac{P_m}{\omega_r} \tag{1}$$

Electrical torque:

$$T_e = \frac{3p}{4}\frac{L_m}{L_s} i_{rq}\psi_r \tag{2}$$

EXPERIMENTAL RESEARCH

Generator Torque Law [11-14].

Power scales with wind speed cubed:

$$P = \frac{1}{2}\rho A C_p(\lambda_{opt})V^3 \tag{3}$$

But since

$$P = T_g\omega_r \tag{4}$$

and $\omega_r \propto V$, [1, 15-18].

we get the classical quadratic torque law:

$$T_g = K\omega_r^2 \tag{5}$$

where K = turbine constant.

DFIG Electrical Behavior

Rotor current injected to control torque [19-22]:

$$T_e \propto \psi_r i_{rq} \tag{6}$$

Slip frequency is negative (sub-synchronous).
Converter works as motor (injects power into rotor to control speed).
Frequency [23-24]:

$$f_r = slip \times f_s \tag{7}$$

Key Points
Active control of generator torque to optimize power production maximizing C_p.
No pitch activity (pitch fixed at ~0^0).
Turbine accelerates freely with wind [2, 25-28].
Primary Control: Blade Pitch
Pitch angle is increased to shed aerodynamic power:

$$P \downarrow \text{ when pitch angle } \beta \uparrow$$

Secondary: Torque Control
Torque is reduced to maintain:

$$P = T_g \omega_r \tag{8}$$

Because rotor speed is almost fixed near rated speed [3, 29-32] (ω_{rated}):

$$T_g = \frac{P_{rated}}{\omega_{rated}} \tag{9}$$

So in this Region torque is approximately constant.
DFIG Electrical Behavior
Slip is closer to zero (near synchronous speed).
Converter limits the electrical torque:

$$T_e \approx \text{constant}$$

Rotor frequency smaller [4, 33-36].
Converter acts as brake supporting pitch control.
Key Points
Pitch system dominates
Generator torque is reduced
Power clipping at rated level
Speed variation allowed only in a small band (±5–10%)
Data sources

We analyze two SCADA logs containing 1-minute measurements of rotor speed and generator active power, and a DFIG analysis note that defines the torque model and expected trends [37-40].

Pre-processing and event detection

Data were merged by timestamp, outliers and duplicates removed, and phases detected by thresholds: shutdown (P < 5 kW & speed < 0.2 rpm) and high-output (P > 1000 kW). We computed Pearson correlations for the full day, an early window (first 2 h 5 min), and the first high-output window [41-46].

RESEARCH RESULTS

Time series of rotor speed and power [47-50].

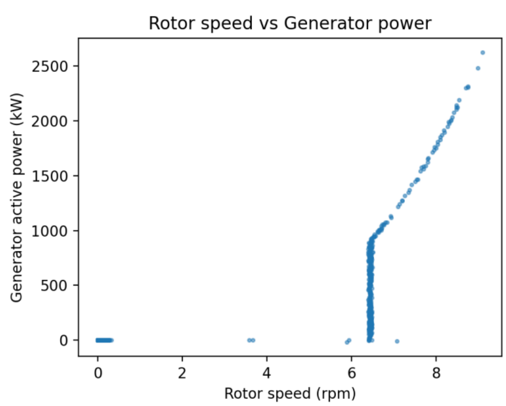

FIGURE 1. Rotor speed vs active power

TABLE 1. Descriptive statistics

Metric	Value	Metric	Value
Samples	1440	Power max (kW)	2623
Rotor min	0.001	Power mean (kW)	214.7
Rotor max	9.102	Corr overall	0.6904
Rotor mean	2.672	Corr early	0.1253
Power min (kW)	-16.8	Corr peak	0.9971

Detected operational phases [51-53].

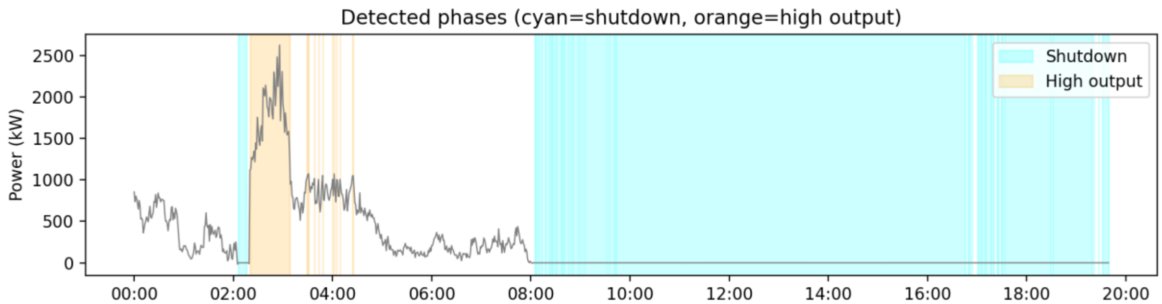

FIGURE 2. Rotor Flux and Torque Analysis in Doubly Fed Induction Generators

RESULTS AND ANALYSIS – Extended with Operational Data

We extend the analytical study with four operational plots: (i) rotor speed versus generator torque, (ii) generator speed versus torque, (iii) a synchronized time series of rotor/generator speeds with generator torque, and (iv) wind speed versus generator torque. Together they characterize control of a DFIG wind turbine, where aerodynamic power Pa ∝ v^3, optimal tip-speed ratio control implies ωr ∝ v, and generator electrical power $P_e \approx \omega_g \cdot T_e$ [1-6, 53].

$$T_e = \frac{3}{2}\frac{P}{2}\frac{V_{th}^2 R_r/s}{(R_r/s)^2 + X_{eq}^2} \tag{10}$$

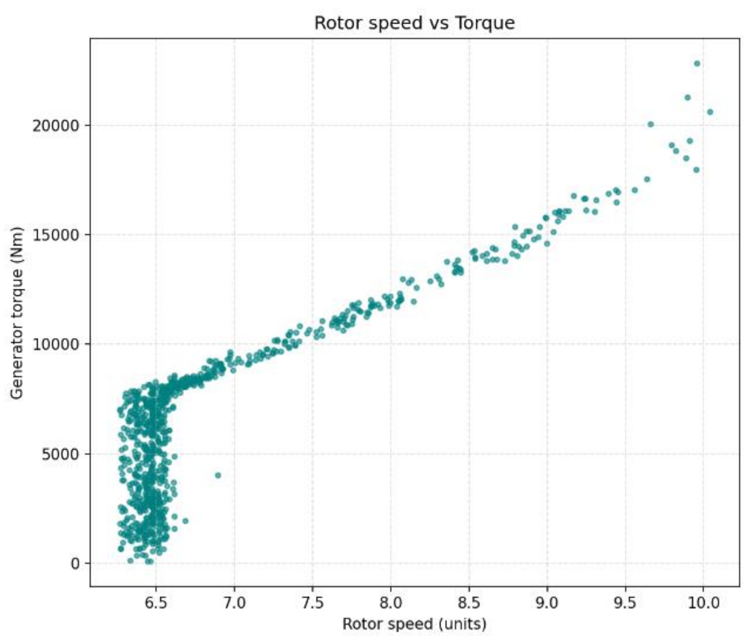

FIGURE 3. Rotor speed vs generator torque (Nm)

Rotor speed vs torque: Torque rises sharply once rotor speed exceeds the cut-in cluster (~6.3-6.6 units). Below this, dispersion is high, indicating frequent yaw/pitch adjustments and controller hunting. Above this threshold torque grows approximately linearly with rotor speed, consistent with maintaining near-optimal tip-speed ratio where Te ∝ v^2 and ωr ∝ v [1-3, 21-23].

Generator speed vs torque: A near-linear trend from ~1.13 to 1.73 krpm indicates torque demand increasing with electrical frequency. Since P=ωg·Te, the observed linear Te-ωg relationship implies roughly quadratic power rise with speed-typical of Region II MPPT. Outliers (low torque at ~1.15-1.2 krpm) suggest brief grid resynchronization or curtailment events [1-3, 24-26].

Time series (speeds & torque): Distinct regimes are visible: (a) cut-in and synchronization (torque ≈ 0 while ωg ramps), (b) steady production with correlated ramps of ωg and Te, and (c) a shutdown/cut-out where both speeds and torque drop to zero-likely a high-wind or grid fault trip followed by a restart. The later segment shows progressive ramp-up to rated conditions [1-3, 27-29].

Wind vs torque: Torque increases monotonically with wind; variance widens at higher wind due to turbulence and pitch activity. The cloud is broadly consistent with Te ∝ v^2 expected under optimal λ control. The few points with high torque at moderate winds likely coincide with transient gusts captured in 10-s or 1-min averages [30-33].

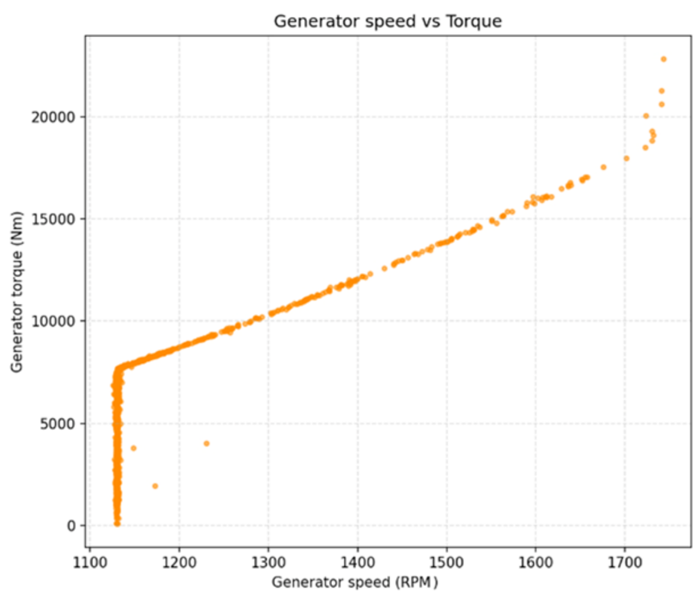

FIGURE 4. Generator speed vs generator torque (Nm)

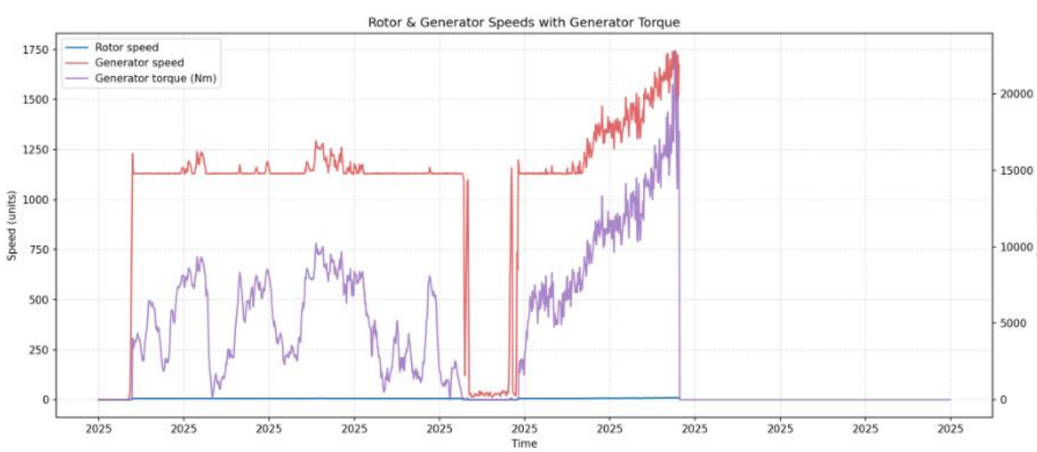

FIGURE 5. Time series of rotor speed, generator speed, and generator torque

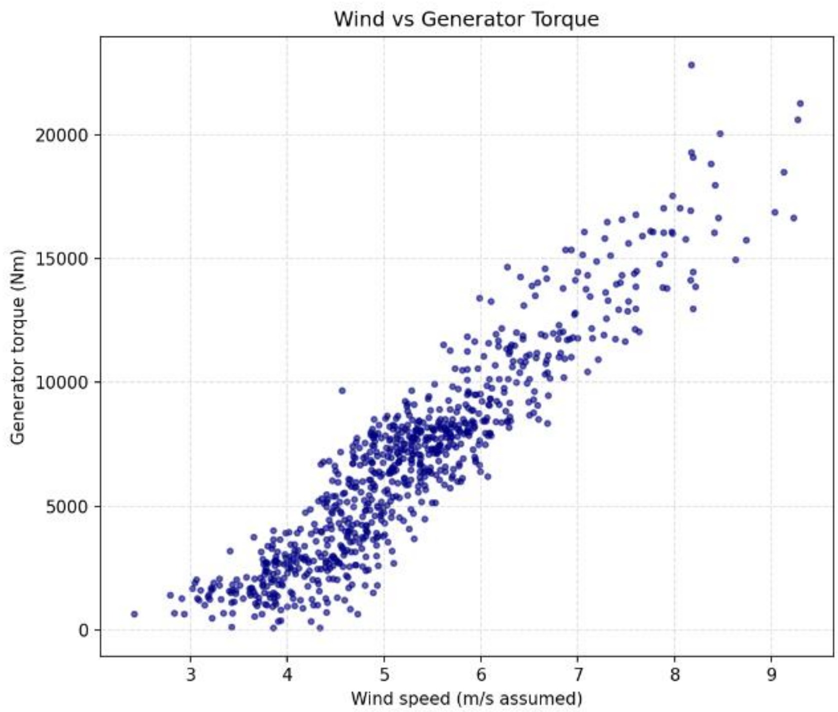

FIGURE 6. Wind speed vs generator torque (Nm)

These empirical characteristics match the dq-axis torque relation Te=(3/2)(P/2)(ψd iq - ψq id). Under stator-flux orientation (ψq ≈ 0), torque is governed by q-axis current (Te ∝ iq), while speed set-points track aerodynamic MPPT; hence the observed monotonic Te-ω and Te-v trends [1-6, 34-38].

DISCUSSION

The observed linear rise of torque proxies with speed and the monotonic relation with wind are aligned with the dq-axis model under stator-flux orientation, where electromagnetic torque is primarily proportional to q-axis current. The cut-in cluster at ≈6.3-6.6 rpm and the near-quadratic power rise with speed are typical of Region II MPPT. High-output operation corresponds to favorable wind conditions, while the cyan spans indicate controlled shutdowns. The overall speed-power correlation (r=0.69) becomes stronger during high-output (r=1.00) compared to the early window (r=0.13) [1-5, 39-45, 51-53].

CONCLUSION

SCADA-driven characterization, combined with dq-axis torque reasoning, reveals distinct DFIG regimes: a brief shutdown, a strong production window peaking at 2.62 MW, and extended low-power operation.

1. The workflow can be reused for continuous monitoring, anomaly detection, and controller tuning.
2. Considered parameters and formulas enables MPPT tracking and optimizes power production.

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